Proceedings of the 2010 International Mechanical Engineering Conference and Exposition
IMECE10
November 12-18, 2010, Vancouver, British Columbia, Canada

IMECE2010-37433

The Use of Potting Materials for Electronic-Packaging Survivability in Smart Munitions

Nien-Hua Chao
U.S. ARMY, ARDEC
Picatinny Arsenal, NJ USA

J. A. Cordes
U.S. ARMY, ARDEC
Picatinny Arsenal, NJ USA

D. Carlucci
U.S. ARMY, ARDEC
Picatinny Arsenal, NJ USA

M. E. DeAngelis
U.S. ARMY, ARDEC
Picatinny Arsenal, NJ USA

S. Marhevka
U.S. ARMY, ARDEC
Picatinny Arsenal, NJ USA

Jyeching Lee
U.S. ARMY, ARDEC
Picatinny Arsenal, NJ USA

L. Reinhardt
U.S. ARMY, ARDEC
Picatinny Arsenal, NJ USA

M. Tesla
U.S. ARMY, ARDEC
Picatinny Arsenal, NJ USA

ABSTRACT

Potted electronics are becoming quite common in precision artillery applications due to demands for increased structural-robustness of these miniaturized smart-munitions. In field artillery applications, the potted electronics are inactive for most of their lifetime where they may have been stored in a bunker without environmental (temperature and humidity) controls for up to 20 years. In contrast, the electronics for most commercial applications tend to be active for most of their lifetimes and the operating environment here is more predictable. This difference makes the thermal management task for the artillery application very challenging. The ability to accurately analyze these designs also requires the use of fully-coupled thermal-stress transient analysis methods and also accurate material properties and strain rates over the full temperature range to be analyzed. To highlight the thermal-stress transient effects the potted configuration of a typical electronics assembly is analyzed. In addition, the structural dynamic responses of un-potted and potted assemblies, subjected to gun launch environments, are analyzed. The results indicate that for the potted design the dynamic response of the processor board is attenuated by the potting material during gun launch, and also some unexpected results, for a hollow cavity device which, fortunately, can be mostly resolved by using some commonly used manufacturing/assembly steps.

INTRODUCTION

Due to the highly dynamic nature of gun launch, many electronic systems resort to potted designs in order to achieve a higher degree of reliability (Ref. 1 through 3). It has been observed previously (Ref. 3) that potting is problematic in the development of reliable munitions. The problems are manifold but the dominant issues revolve around the temperature dependency of the electronic components and also the potting material itself. Variations in temperature greatly affect structural properties, induce thermal expansion mismatch stresses, and also influence the dynamic behavior of the design. As finite element analysis capabilities advance more insight is being gained as to dynamic behavior and, as will be discussed and illuminated in this work, a particularly troublesome aspect of a potted design transient thermal-stress response.

Thermal management has always been very important for the electronic-packaging industry. In the 80s', the commercial finite element model (FEM) programs (ANSYS, MARC) were available on the DEC VAX-11/780 and Cray. In the late 1980s and early 1990s, when the PC 286/386 with extended memory became affordable, commercial FEMs (e.g. ANSYS) started using analyses to assist with the thermal management of electronic packaging (Ref. 4 and 5). During that time, FEM-program user-interfaces were very basic. It was also very difficult to properly mesh a design with only a few part stack-ups in the *z*-direction (it is still a very useful tool to simulate 2-1/2 D problems). During the 1980s, research in the area of contact mechanics (Ref. 6 and 7) offered a new approach to handling the contact-interface between parts with different meshes and the misalignment of nodes between adjacent part surfaces. Today, the contact/tie-element has become a standard feature in the commercial FEM programs and, together with increased CPU-processor speeds and large amounts of available on-board memory, it is much easier and faster now to perform a fully coupled thermal-stress transient simulation for a complex electronic packaging system.

With these advances in computational capabilities, The United States Army Armament Research, Development and Engineering Center (ARDEC), Picatinny Arsenal, New Jersey has developed models to examine the transient dynamic behavior of smart munitions.

SMART MUNITIONS TREND AND ARDEC TECHNOLOGY NEEDS

During the past couple of years, NATO has organized a lecture series on technology trends in the area of MEMS applications.

Table 1 shows the challenges that military platform development efforts face by using commercial/civil MEMS products. Military applications tend to require lower quantities compared to commercial applications. Figure 1 depicts a system technology roadmap of the progression and miniaturization of systems utilizing MEMS-devices (while most of these systems have been demonstrated as actual hardware, the 2 in^3 volume Inertial Measurement Unit (IMU) is just now being realized where more work is still needed in achieving the performance levels stated). Table 2 shows typical environments for tank, artillery, missile, and mortar munitions.

Table 1 Extract From (Ref. 8)
RTO-EN-AVT-105 P 4-11

The Challenges – Inertial Measurement Units:

Whilst the important role of MEMS is confirmed for future military platforms, further developments in the design and performance of these devices is, however, necessary in order to satisfy the stringent requirements set for military applications. More specifically (and typically):

•Military specifications are particularly demanding (for example):

Temperature:	**-65°C to > +125°C**
Mechanical shock:	**more than 15,000g for gun launched munitions**

Other, more generic, challenges will also need to be addressed, namely:

•Military MEMS will depend, heavily, on the commercial or civil MEMS developments as low volumes, for the military markets, will attract high costs.
•Military product life-cycles exceed those for commercial or consumer products where, both process availability and product obsolescence become a major concern.

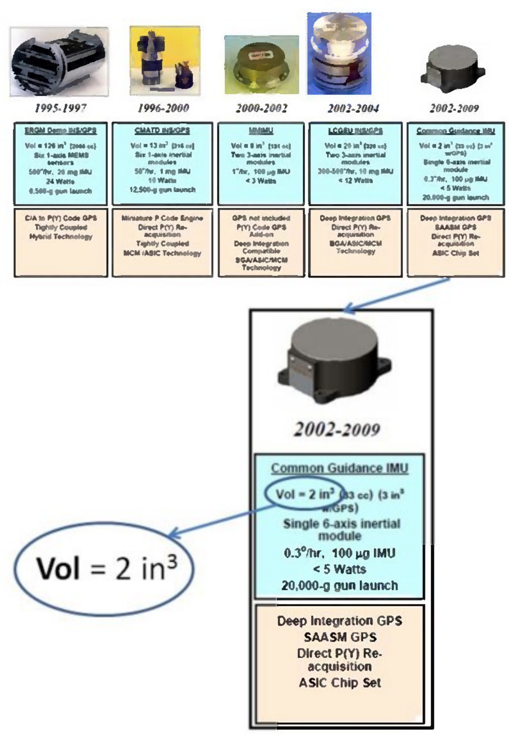

Figure 1. Inertial MEMS System Applications – System Technology Roadmap **(Extract From Ref. 9)**

Table 2 Shows typical environments for tank, artillery, missile, and mortar munitions **(Extract from Ref. 9)**

	Units	Tank (120 mm)	Artillery (155 mm)	Missile	Mortar (4.2")
Launch Conditions					
-- Chamber Pressure	ksi	80	60		15
-- Max Axial Launch Acceleration	g	100K	20K	500	10K
-- Max Radial Launch Acceleration	g	10K	2K	50	1k
-- Angular Rotation In-Bore (Twist)	rev/cal	0	1/20	0	1/20
-- Motor/Propellant Temp	K	300	3000	3000	3000
-- Time In-Bore	ms	7-10	10-20		5
Flight Conditions					
-- Base Pressure	ksi	20	20	20	20
-- Max Axial Flight Accel (Drag)	g	-5	-10	-20	-5
-- Max Radial Flight Accel	g	0.50	0.50	2.00	1
-- Angle of Attack	degrees	±5	±15	±15	±15
-- Structural Vibrations	KHz	10	10	10	10
-- Roll Rate	Hz	0-60	100-300	0-60	0-130
-- Yaw/Pitch Rate	Hz	0-10	0-40	0-10	0-40
-- Time In-Flight	s	10	200	1000	30

Ref 8 Brown et al, "Strap-Down Micromechanical (MEMS) Sensors for High-G Munition Applications", IEEE Transactions on Magnetics, Jan 2001

With this in mind, it is imperative for the ARDEC R&D organization to start the efforts of performing Fully-Coupled Thermal-Stress Transient Simulations of the Potted Smart Munitions.

A FULLY-COUPLED THERMAL-STRESS TRANSIENT SIMULATION

In this study, we have created a test potted package with one MEMS , one Leadless Ceramic Carrier (LCC) - a hollow cavity device, a printed circuit board (PCB), a processor board, support frame structure, can, and cover. In order to get a better understanding of the test potted package thermal performance during the Highly Accelerated Life Testing (HALT), the ABAQUS FEM program (Ref. 10) was used to model and conduct the fully-coupled thermal-stress transient simulation. A pictorial view of the potted test package is shown in Figure 2.

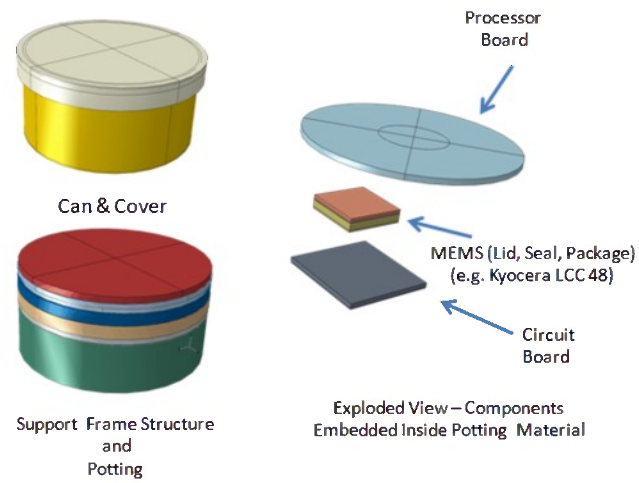

Figure 2. FEM model of a MEMS attached to PCB, frame, can, cover and potting material.

Figure 3 depicts the finite-element mesh of the model. It is important that an effective thermal conduction model is constructed in order to produce the proper fully-coupled thermal-stress transient simulation results. It is a very tedious task to tie all of the part/surface interfaces in the proper way so as to obtain the correct results. It is equally important to obtain the correct thermal-transient-related material properties to include in the model.

An understanding of the assembly procedure for each of the devices is also essential (Ref. 11 and 12) so that one can create an accurate model for simulation. The simulation and understanding the potted packaging thermal performance is very important because the use of commercial-grade products for defense applications (Ref. 8) - The product may work fine in a commercial application (Ref. 1) but may then fail miserably due to the harsher environments of a military-application, e.g., being subjected to extremely high-G accelerations during a gun launch. Communication with the original LCC package suppliers may also be necessary to obtain critical material-strength properties and physical-characteristics of their products that have determined to be important for maximum strength and robustness. Appendix I illustrates the information that was the result of an independent communication with Kyocera who is a major supplier in the electronic packaging world.

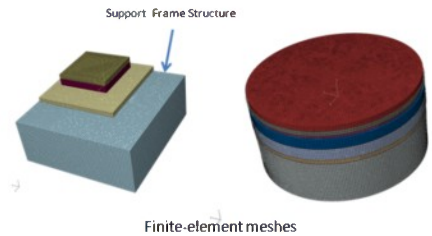

Figure 3. FE meshes for LCC, PCB, support frame, and potting material

Figure 4 depicts the HALT temperature profile that was applied to the outside surface of the potted package and which serves as the boundary conditions for the thermal-stress transient simulation. This HALT profile is part of a thermal-cycle test that is conducted during development of the potted package to ensure that it will function properly after the projectile has been in storage and experiencing adverse temperature conditions for a long period of time.

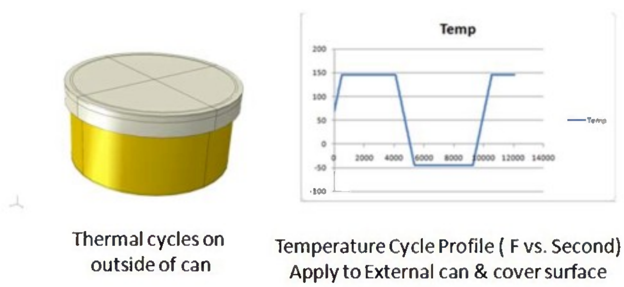

Figure 4. HALT (Highly Accelerated Life Test) temperature profile

BENEFITS OF PERFORMING A FULLY-COUPLED THERMAL-STRESS TRANSIENT SIMULATION

The results from performing a fully-coupled thermal-stress transient simulation are very useful for providing a better understanding of the potted package performance during the HALT process which might not be easily obtainable through experimental testing (either due to instrumentation difficulties, time/cost constraints, and where only limited models can be built).

The basic assumption is that we can create a finite-element model which closely mimics real-product behavior. The stress levels at the seal layer, as well as the solder-joints, are critical performance characteristics of the product. In Figures 5 to 8, the stress patterns and displacement of the seal layer are chosen to illustrate that these stresses/deformations can be produced due to the CTE-mismatch between different materials as well as temperature gradients during the HALT process. These are the critical design aspects that must be effectively managed for reliable thermal-stress transient product performance. The shear stresses may cause seal layer (the seal between the Lid and the Package) failure during the HALT process. The deformation changes (from Figures 6 to 7 at time ~460 s and time ~5160 s) on the seal layer during the HALT process could be an indication that a low-cycle fatigue failure in the seal layer is a possibility during long-term storage.

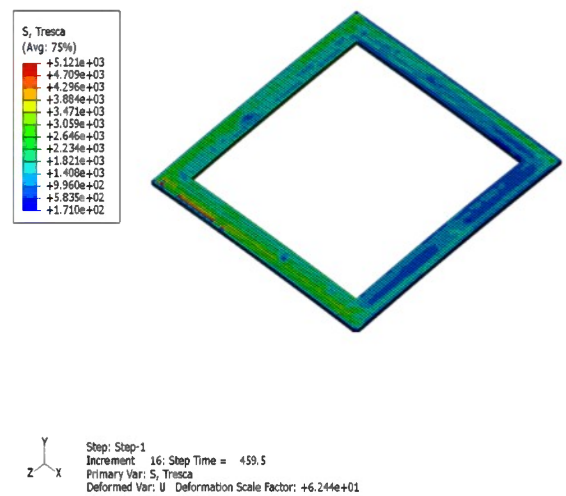

Figure 5. Shear stresses at the seal layer at time-step 459.5sec. during the HALT process

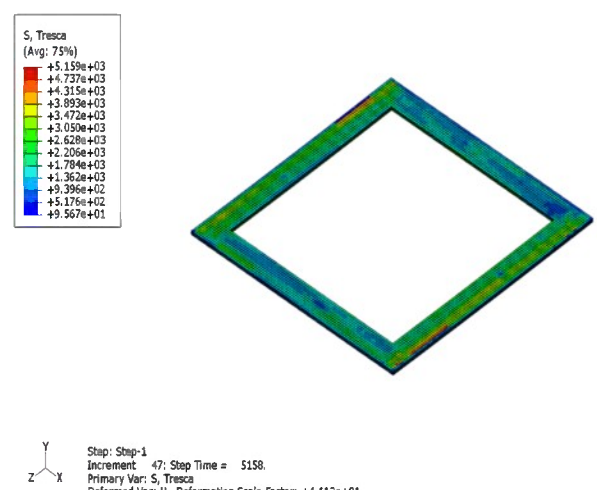

Figure 6. Shear stresses at the seal layer at time-step 5158sec. during the HALT process

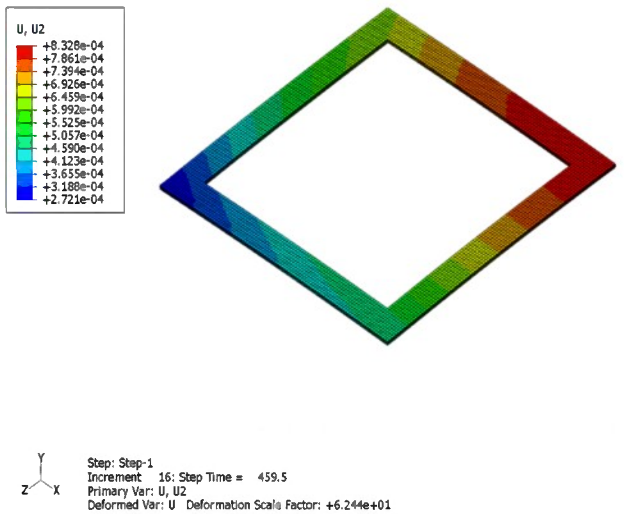

Figure 7. Deformation magnitude differences (Y-direction) at time-step 459.5sec. during the HALT process

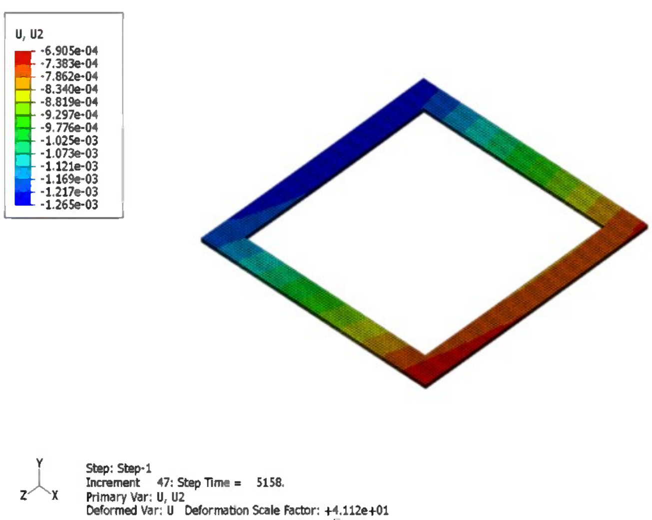

Figure 8. Deformation magnitude differences (Y-direction) at time-step 5158sec. during the HALT process.

POTTED VS. NON-POTTED DESIGN COMPARISON

When the applications of miniaturized MEMS to the field artillery with potted electronics, this created additional challenges to the electronic-packaging analysis and simulation team. Many designs utilize potting because miniaturization of smart munitions, from missiles to fielded-artillery weapon systems, has provided less space to implement designs that are robust both structurally and dynamically. With tighter design-spaces, the use of bolts or screws, to join and rigidly fix together individual parts, becomes increasingly difficult. With ever-tighter design-spaces the job of the electronics designer becomes very challenging; to not only design circuits with the correct functions but to also design the circuit boards and other electronics so that they connect to one another in a robust and well-supported fashion. The use of potting materials, to help support and protect miniaturized electronic designs against high launch-forces, therefore becomes a very attractive design-solution. The presumed ease of assembly, coupled with the assumption that the load will be well distributed makes one think that potting is a very simple approach. If we can manage the thermal performance of potted electronic-packaging designs, we would therefore have a win-win solution.

A word of caution is warranted here – in ANY design the potting materials need to be well-characterized over temperature and strain rates. This does not mean to simply rely on the information from a manufacturer's data sheet. This is usually woefully insufficient and often inaccurate. The material has to be tested for mechanical strength, thermal expansion characteristics, curing shrinkage, adhesion to surfaces, and also creep over the full temperature range and at different strain rates. Without this data a potted design should not be attempted.

Two examples were examined to illustrate the processor board deflections during a Gun-Launch simulation; the first is an un-potted design while the second is a potted design. These two examples each include a processor board, one MEMS mounted on a PCB, a support frame structure, and a can with cover (Figure 4). A more detailed description of each case is as follows:

Case 1: The processor board is supported underneath, on its circumference, by a small steel support-ring which is attached to the inside-can surface - no potting material is used inside the test package.

Case 2: The processor board is supported underneath by potting material. The potting material has the following properties: Young Modulus (E): 90,000 psi., mass density: 1.40E-04 (lbf s2/in4).

Figures 10 show plots of the Gun Launch Accelerations applied to the bottom of the Can surface (shown in Figure 9). During the gun-launch simulation, the distances from the bottom-center of the Can to the center-point of the processor board (bottom surface), and the center-point of the LCC lid (top surface), were recorded (shown in Figure 11). By comparing the results from the Case 1 and Case 2 simulations (Figures 12 to 15), we see that the potting material provided greater support and thus reduced the processor-board deflection magnitude by a factor of ten during the set-back (in-barrel) phase, and a factor of four during the set-forward (muzzle exit) phase (from ~0.060” to ~0.006” during set-back, and from ~0.021” to ~0.006” (peak-to-peak) during set-forward). [Set-back is defined as the forward acceleration of the projectile-mass due to rapidly increasing base-pressure from burning of the propellant. Set-forward is defined as the rapid structural-unloading of the projectile (i.e. "unspringing" of the compressed projectile structure) as it exists the muzzle and the base-pressure drops off]. In Figures 13 and 15 the results also show that the potting material can be used as a vibration dampener due to its energy-absorption characteristics. The high frequency energy was attenuated by the potting material.

Figures 16 shows the overlays of the displacements of the processor boards for both the with/without potting cases. Figure 17 shows the overlays of the displacements of the MEMs lids for both the with/without potting cases. However, the addition of the potting material appears to have also increased the motion of the MEMS’s lid during the projectile’s set-back and set-forward phases (from ~0.002” to ~0.009” during set-back, and from ~0.001” to ~0.006” (peak-to-peak) during set-forward). [The set-forward portion of a projectile’s transit through the gun is known to cause a large proportion of the failures in electronic systems]. In the finite-element model, the bonding technique that was used between the devices and the potting material was perfect-tight contact. This type of contact was used to model the additional displacement that can occur, during the set-forward event, should the potting material adhere well to the electronic devices and other structures. The use of a conformal coating, or a mold release agent, applied to the lids of hollow-cavity and other critical devices, before potting, should help prevent the potting from adhering to these areas–(this approach is also suggested in thermal-stress simulation discussion section).

While potting materials offer the ability to simplify electronic packaging designs, while also providing for increased structural and dynamic support, we must also be careful in their selection and use so as to produce reliable designs that can also survive the thermal environments that they will see not only during HALT testing but also during their lifetimes as well.

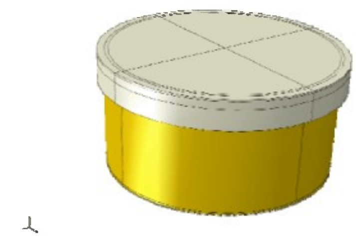

Figure 9. Gun-launch acceleration boundary conditions (Ref. 13) – Applied to the Can bottom surface

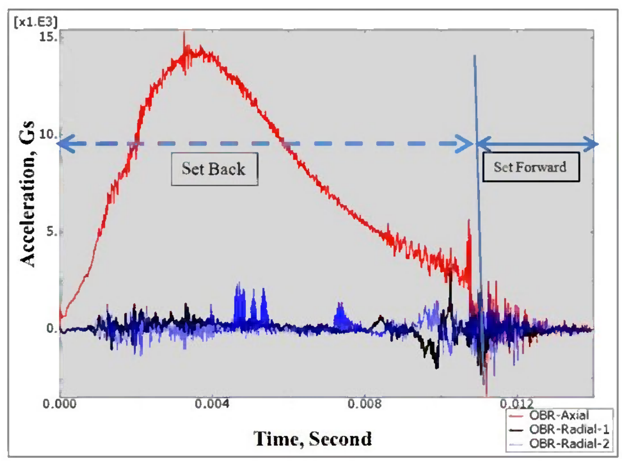

Figure 10. Axis-Y Acceleration

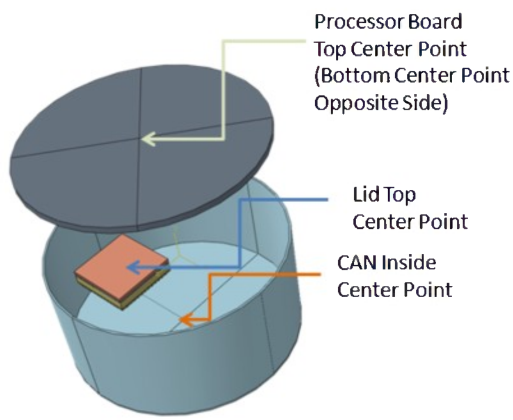

Figure 11. Dynamics simulation displacement data collection points

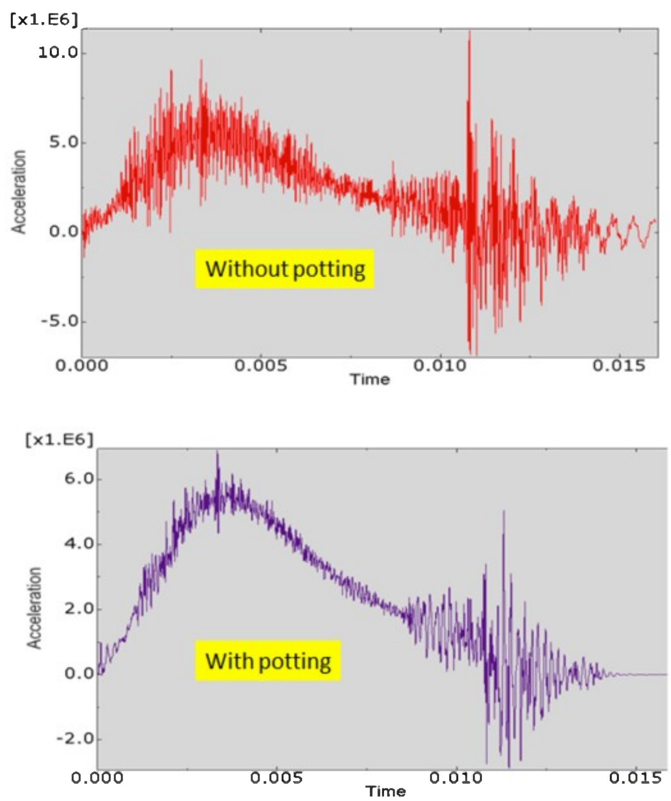

Figure 12. The acceleration responses (y-axis) for the processor board for both with/without potting material

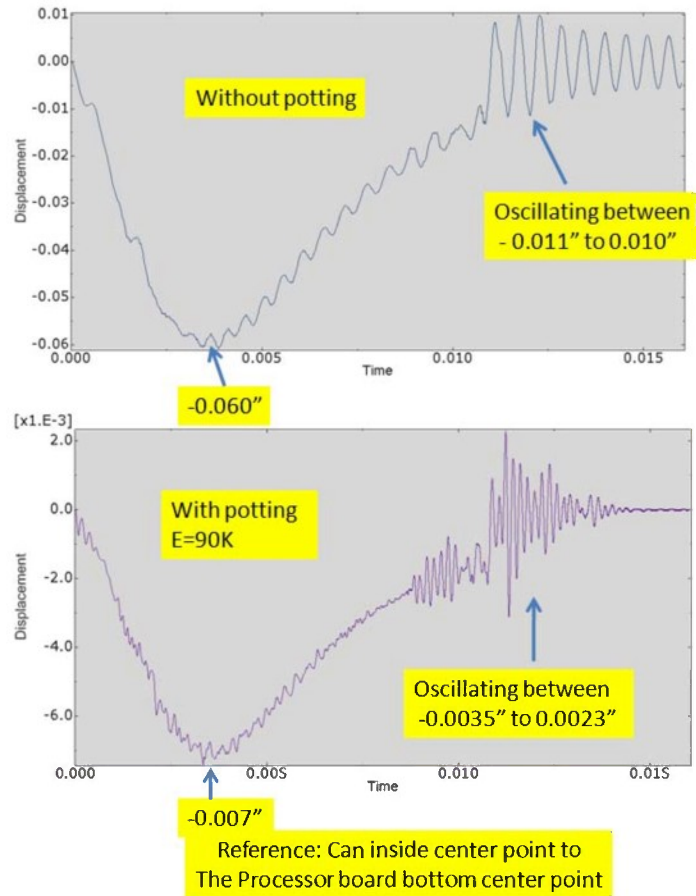

Figure 13. The relative-distance changes between the bottom center point of the processor board and the center point of the can inside center point

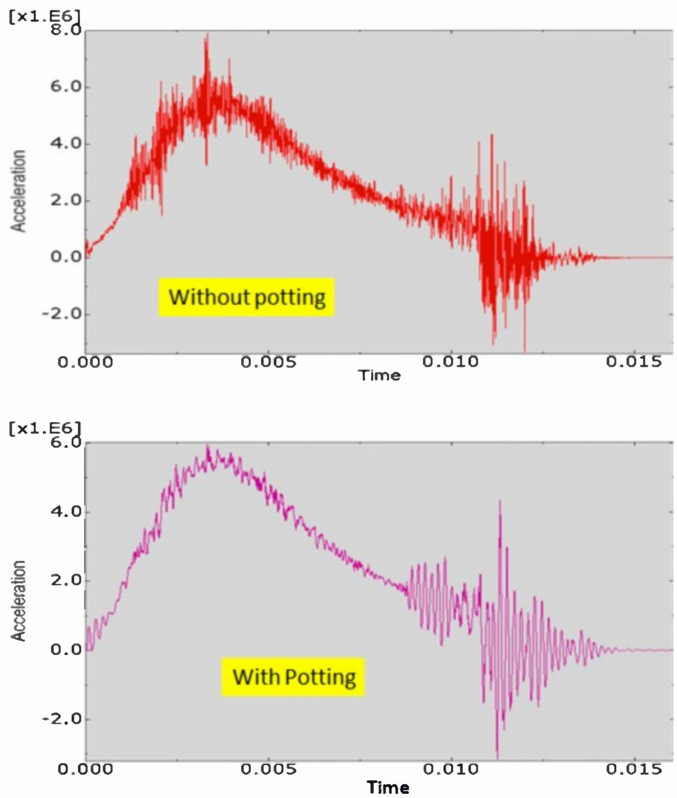

Figure 14. The acceleration responses (y-axis) for the Lid center point for both with/without potting material

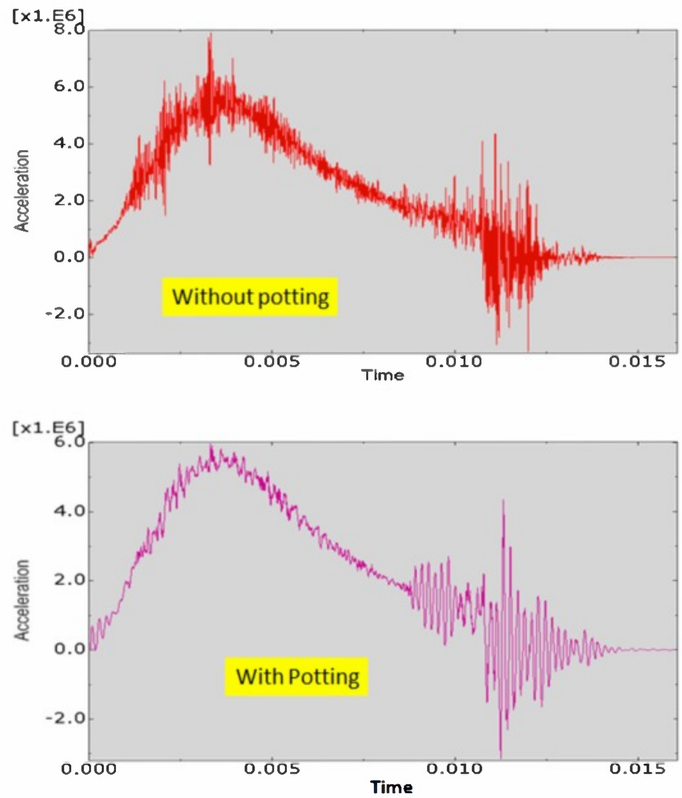

Figure 15 . The relative-distance changes between the center point of the lid top surface and the center point of the can inside center point

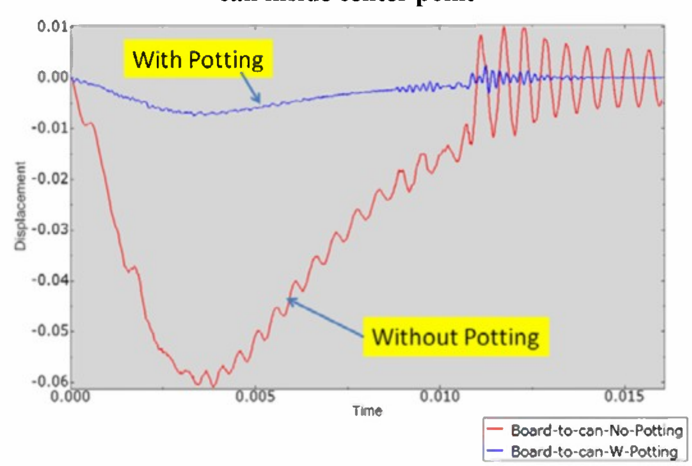

Figure 16. Overlay displacements of the processor boards from Figure 13

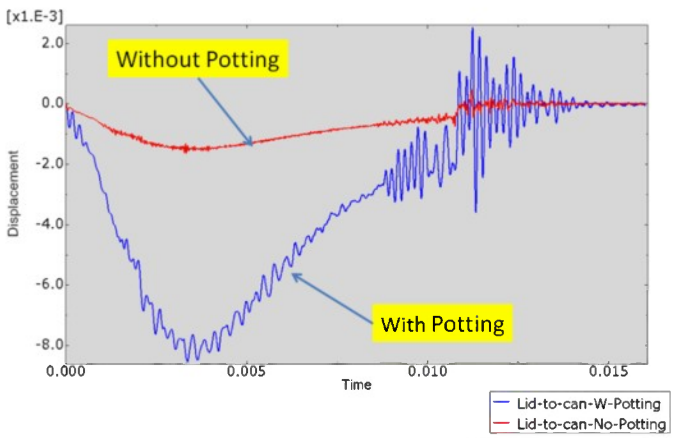

Figure 17. Overlay displacements of the MEMS lids from Figure 15

CONCLUSIONS

With the recent advances in MEMS technology, and its increased use in smart munitions for field-artillery, we expect to see more product development problems associated with potting these devices and the issues here to be thermal and transient in nature.

It has been shown in this study:

- A fully-coupled thermal-stress simulation is a valuable and necessary tool to aid the product development process for evaluating MEMS-based, artillery projectile designs, due the criticalness of small features (the seal layer thickness of the MEMS device analyzed here was only 0.003" to 0.006" thick making it impractical to embed sensors, or use some other stress-monitoring technique).
- It is critical to understand and manage the thermal performance of devices in artillery projectile designs. Devices here are ***inactive*** and in storage for most of their lifetimes (up to 20 years) with no controls on environmental conditions (both temperature and humidity). The devices (MEMS) within the projectile will therefore be subjected to daily ambient temperature fluctuations, and low-cycle fatigue stresses, which could lead to eventual failure of the devices.
- To support efficient and accurate modeling of future designs it is important to quickly establish and maintain accurate temperature and strain rate dependent properties of the various critical materials and compositions (including potting materials).

ACKNOWLEDGEMENT

The authors would like to express their appreciation for the support provided by our colleagues Ms. Shana Groeschler, Dr. Aisha Haynes, Mr. Pasquale Carlucci, and Mr. Nicholas Payne. In addition, we would like to thank the Kyocera U.S support team; Mr. Jake Morikami, Mr. Trey Price, and Mr. Kazuhito Kanazashi, for the information they provided.

In addition, the authors would like to also thank Mr. Stuart Cooper of AIS for his suggestions and recommendations provided during the review of this manuscript.

REFERENCES

1. D. Carlucci, J. A. Cordes, J. Hahn, A. Frydman, Electronics and the Gun Environment, Invited Paper, U.S. Army Workshop on Advanced Active Thin Film Materials for the Next Generation of Meso-Micro Scale Army Applications, May 2005.

2. D. Carlucci, J. Cordes, S. Morris, R. Gast, Muzzle Exit (Set Forward) Effects on Projectile Dynamics, Technical Report ARAET-TR-06003, U.S. Army Armament Research Development and Engineering Center, Dover, NJ, April 2006.

3. D. Carlucci, R. Pellen, J. Pritchard, W. Demassi, Smart Projectiles: Design Guidelines And Development Process Keys To Success, Technical Report in publication process, U.S. Army Armament Research Development and Engineering Center, Dover, NJ, date TBD.

4. N. H. Chao and K. E. Wolf, Finite-Element Thermal Analysis and Experimental Tests of a 150W Board Mounted Power Module, TM-11138-930430-08 AT&T Bell Laboratories, April 29, 1993.

5. N. H. Chao and J. Yuan, Analysis of Local Deformation in Internal Layers During Multilayer Board Lamination, Proceedings of IPC Semiannual Meeting, The Institute for Interconnecting and Packaging Electronic Circuits, October 25, 1993.

6. G.M.L. Gladwell, Contact Problems in the Classical Theory of Elasticity, Sijthoff and Noordhoff, 1980.

7. K.L. Johnson, Contact Mechanics, Cambridge University Press, 1985, Cambridge, England.

8. Ayman El-Fatary, “Inertial Measurement Units – IMU”, NATO RTO ACT Lecture Series on “MEMS Aerospace Applications”, ETO-EN-AV-105, March 2003.

9. N. Barbour, R. Hopkins, A. Kourepenis, P. Ward, “Inertial MEMS System Applications”, NATO Lecture Series, 116 in Oct./Nov. 2008 and March. 2009.

10. ABAQUS Analysis User's Manual, Version 6.9-EF1.

11. Kyocera Standard Specifications of CERDIP, No. BS-2001 Rev. C, November 1987.

12. Kyocera Standard Specification for SMD Packages, AS-1005 Rev. A, Oct. 15, 1999.

13. J.A. Cordes, D. E. Carlucci, J. Kalinowski, L. Reinhardt, "Design and Development of Reliable Gun-Fired Structures”, ADA-455406, June 2006

APPENDIX - I
KYOCERA RECOMMENDED SEAL METHOD AND CORRESPONDING SEAL STRENGTH